

TRADE-SPACE EXPLORATION COMPARISON OF PARAMETRIC COST MODELS FOR SATELLITE ANOMALIES WITH RMSE AND RRMSE

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ABSTRACT: Satellites are essential for modern communication, navigation, and Earth observation, but their operation in the harsh space environment makes them vulnerable to anomalies and failures, resulting in significant financial losses. This research investigates the relationship between the design life of satellite subsystems and the cost of anomalies, using data from the Seradata database. Three statistical models, Exponential, Weibull, and Poisson distributions, were applied to cost data for four critical subsystems: antenna, payload, power system, and attitude control. Each model was fitted using one-variable (cost only) and two-variable approaches (design life and cost) to evaluate subsystems' behaviour independently and in combination. The performance of each model was assessed using the Root Mean Square Error (RMSE) and the Relative RMSE (RRMSE). Among all models, the Exponential distribution consistently produced the best results. For instance, the payload subsystem achieved the lowest RMSE and RRMSE of 115.73 and 41.66% in the two-variable case. Similarly, the attitude control subsystem showed strong performance with an RMSE of 110.57 and RRMSE of 40.59%. In contrast, the Poisson distribution yielded the highest errors across most subsystems, with the antenna subsystem reaching an RMSE of 489.87 and RRMSE of 102.65% in the two-variable fitting. The Weibull model demonstrated mixed performance, performing moderately for the payload subsystem (RMSE 186.21, RRMSE 67.03%), but poorly for the power system and antenna subsystems, particularly when two variables were used.

ABSTRAK: Satelit memainkan peranan penting dalam komunikasi moden, navigasi, dan pemerhatian bumi, namun operasinya dalam persekitaran angkasa lepas yang ekstrem menjadikannya terdedah kepada anomali dan kegagalan, sekali gus membawa kepada kerugian kewangan yang besar. Kajian ini mengkaji hubungan antara jangka hayat reka bentuk subsistem satelit dengan kos anomali menggunakan data daripada pangkalan data Seradata. Tiga model statistik iaitu taburan Eksponen, Weibull, dan Poisson telah digunakan pada data kos bagi empat subsistem kritikal: antena, muatan, sistem kuasa, dan kawalan sikap. Setiap model dipadankan menggunakan pendekatan satu pemboleh ubah (kos sahaja) dan dua pemboleh ubah (jangka hayat reka bentuk dan kos) bagi menilai tingkah laku subsistem secara individu dan gabungan. Prestasi setiap model dinilai menggunakan Ralat Punca Min Kuasa Dua (RMSE) dan Relatif RMSE (RRMSE). Antara semua model, taburan Eksponen secara konsisten memberikan dapatan terbaik. Sebagai contoh, dalam subsistem muatan, ia mencapai nilai RMSE dan RRMSE terendah iaitu 115.73 dan 41.66% masing-masing bagi kes dua pemboleh ubah. Begitu juga, subsistem kawalan sikap menunjukkan prestasi kukuh dengan RMSE 110.57 dan RRMSE 40.59%. Sebaliknya, taburan Poisson menghasilkan ralat tertinggi

dalam kebanyakan subsistem, dengan subsistem antenna mencatatkan RMSE 489.87 dan RRMSE 102.65% dalam padanan dua pemboleh ubah. Model Weibull pula menunjukkan prestasi bercampur, sederhana dalam subsistem muatan (RMSE 186.21, RRMSE 67.03%) tetapi lemah bagi subsistem sistem kuasa dan antenna, khususnya apabila dua pemboleh ubah digunakan.

KEYWORDS: *Parametric cost mathematical models, satellite anomalies, trade-space exploration, Exponential, Weibull, Poisson, RMSE, RRMSE*

1. INTRODUCTION

Satellites are essential to modern communication, navigation, and Earth observation systems. However, operating in extreme space conditions makes them prone to anomalies and malfunctions, which can lead to substantial financial losses [1]. This research examines the relationship between failures in key satellite subsystems, including attitude control, power systems, payloads, and antennas, and their associated costs. By applying Trade-Space Exploration (TSE) in combination with statistical modelling, the study analyzes data sourced from the Seradata database [2]. Using MATLAB, cost models are developed using Exponential regression to capture compounding risk factors, Weibull distributions to represent failure rates over time, and Poisson distributions to model the frequency of discrete anomaly events. The central issue addressed is that many existing cost models overlook nonlinear cost escalation, the financial impact of insurance claims, and probabilistic predictions of anomalies [3]. Traditional models often oversimplify the complex trade-offs between design life, performance, and operational cost, making it difficult for satellite operators to make informed decisions [3]. Thus, this study addresses these shortcomings by integrating parametric cost modelling and evaluating model performance using Root Mean Square Error (RMSE) and Relative RMSE (RRMSE) to assess accuracy. Such an approach is crucial for enhancing space situational awareness and supporting efforts to minimize space debris from malfunctioning or failed satellites [4].

2. SATELITE SUBSYSTEMS FAILURES

Understanding subsystem vulnerabilities is key to analyzing satellite anomalies, as some components are more susceptible to failure than others, which often leads to major operational setbacks and financial implications. Data sourced from Seradata highlights four subsystems with the highest recorded anomaly rates: the power system, attitude control system, payload system, and antenna subsystem [2]. Each of these plays a critical role in the satellite's overall performance, and their tendency toward failure points to the need for targeted design improvements and robust monitoring methods.

The power system, which comprises solar panels, batteries, and distribution electronics, is crucial for sustaining satellite operations. Failures in this area can range from reduced solar panel efficiency to total battery malfunction [2, 5]. Solar panels often suffer damage from micrometeoroid impacts or gradually lose efficiency due to prolonged exposure to radiation. Batteries, meanwhile, are vulnerable to thermal cycling and overcharging, which can diminish their capacity or even cause catastrophic failure [6]. Notably, intense radiation events have been known to cause either temporary disruptions or irreversible harm to these power subsystems, significantly shortening mission duration [2, 5].

The attitude control system (ACS) maintains the satellite's proper orientation in space. It ensures that instruments and communication links are accurately directed and solar panels receive optimal sunlight. Failures within the ACS, especially in components like reaction

wheels, can cause a loss of orientation, making it impossible for the satellite to perform essential operations [2, 6]. Reaction wheels are prone to mechanical wear and friction-based issues, particularly over extended periods, and failure in one or more of these components can compromise the mission. Because these problems are challenging to address once the satellite is in orbit, real-time telemetry and early-warning systems are critical for managing ACS health [7].

The payload system, which differs based on the satellite's function (such as imaging, communication, or scientific research), is essentially the heart of the mission. Payload failures may stem from various sources, including extreme temperature shifts, vibrations during launch, or radiation damage to sensitive instruments [5, 8]. In communication satellites, for example, amplifier degradation can weaken signal strength or disrupt data transmission altogether [2, 5].

Finally, the antenna subsystem sends and receives signals between the satellite and Earth. This system is vulnerable to mechanical issues like misalignment, wear and tear, and damage from space debris or radiation exposure [2, 9]. Misalignment can reduce communication efficiency, resulting in data loss or operational delays. Smaller satellites that rely on deployable antennas face additional risk; these antennas can malfunction during deployment, potentially crippling the satellite's communication capabilities [2, 5].

3. RESEARCH METHODOLOGY

This section presents the methodology adopted to explore the trade-space between satellite subsystem design life and anomaly-related costs using traditional mathematical modelling, to determine how varying design life values influence financial losses, and identify cost-effective configurations through a structured process encompassing problem identification, data gathering, visualization, model fitting, evaluation, and trade-space analysis.

3.1. Dataset

The dataset used in this study was obtained from the Seradata database, which documents satellite missions and their associated anomalies [2]. Only records involving satellites that experienced one or more subsystem anomalies were considered. Each data entry includes the design life and corresponding anomaly cost for four specific subsystems: antenna, payload, power system, and attitude control. About 87 satellite cost data points ranged from LEO, MEO, and GEO orbits. The cost values represent the total financial loss, including the satellite's manufacturing cost and any insurance claims resulting from the anomaly [2]. Table 1 tabulates the Seradata components. The values are concealed due to confidentiality reasons. Seradata advised the researchers not to reveal the values. The reason is that some satellite companies are not keen to reveal specific cost values.

Table 1. Seradata Components

Subsystems	Design Life (years)	Cost (US\$m)
Antenna	15	XXX

Payload	10	XXX

Power System	5	XXX

Attitude Control	13	XXX

3.2. Parametric Cost Models

Based on the nature of the data and the goal of analyzing cost trends relative to reliability, three mathematical distributions commonly used in reliability engineering were selected: the Exponential, Weibull, and Poisson distributions. These models were chosen for their ability to capture the behaviour of failure rates and lifetime costs in complex systems [10, 11]. Each model was applied to the cost versus design life data of each subsystem separately to identify the distribution that best describes the cost pattern. The three models, namely the Exponential, Weibull, and Poisson, are defined in Eqs. (1), (2), and (3), respectively.

$$f(x) = ae^{-bx} \quad (1)$$

where x denotes the design life of the subsystem, a and b are the model parameters.

$$f(x) = abx^{(b-1)}e^{-(ax^b)} \quad (2)$$

where x denotes the design life of the subsystem, a is the cost scale, and b is the Weibull parameter.

$$f(x) = \frac{e^{-a}a^x}{x!} \quad (3)$$

where a denotes the rate parameter and x is the number of failures.

The modelling process was then done using MATLAB, which provided tools for curve fitting, parameter estimation, and visual validation. The design life and cost data for each subsystem align with the three selected models. The resulting model curves were plotted alongside the actual cost data to observe the level of agreement between predicted cost and observed cost values. MATLAB's built-in functions were employed to extract model parameters and evaluate the statistical quality of each fit.

3.3. Cost Models Performance

To assess the accuracy and effectiveness of each fitted model, two key error metrics were used: Root Mean Square Error (RMSE) and Relative Root Mean Square Error (RRMSE) [12]. RMSE measures the absolute difference between the predicted and actual cost values, indicating the model's prediction error [13]. RRMSE, on the other hand, expresses the error as a percentage relative to the mean of the observed values, offering a normalized measure that facilitates comparison across different subsystems or scales [14, 15]. The model with the lowest RMSE and RRMSE for a given subsystem was considered the best-fitting model. These metrics played a crucial role in identifying which distribution most accurately captured the cost-design life relationship [16, 17]. The RMSE and RRMSE equations can be defined in Eqs. (4) and (5).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Observed\ Cost - Predicted\ Cost)^2} \quad (4)$$

$$RRMSE = \frac{RMSE}{Mean\ of\ Actual\ Cost} \times 100 \quad (5)$$

3.4. Trade-Space Analysis

Following model fitting and evaluation, a trade-space analysis was conducted to assess the impact of variations in subsystem design life on the overall cost of anomalies [18, 19]. Both one-variable and two-variable fitting approaches were used during this process. The one-variable fitting focused on the relationship between design life and cost for individual subsystems, allowing for a clearer understanding of how each subsystem behaves

independently [17, 20]. In contrast, two-variable fitting considered the interaction between design life and cost across multiple subsystems simultaneously, offering a broader view of how combined subsystem behaviour influences overall cost trends. This approach was necessary to capture both isolated and interdependent effects on cost [21]. The analysis helped to identify critical points where extending the design life no longer leads to proportional cost savings, thus revealing optimal design zones [21, 22]. These insights contribute to making informed decisions on allocating design resources efficiently while balancing reliability and cost considerations [23, 24].

4. RESULTS

The graphical representations for Exponential, Weibull, and Poisson distributions, both one-variable and two-variable, can be found in Figures 1 and 2, respectively. From Figure 1, the cost data analyzed through Exponential curve fitting reflects the financial consequences of satellite subsystem anomalies. Among the subsystems, the antenna-related anomalies exhibited the steepest Exponential rise in cost, with values ranging from US\$160.7 million to US\$945 million, and an average of US\$477.2 million. This sharp increase underscores the growing criticality and complexity of antenna systems, where even less frequent failures can result in extremely high financial losses. Such trends may be due to the critical role of antennas in communication and navigation, where in-orbit failures are difficult and costly to rectify [25]. In contrast, the payload subsystem showed a decreasing Exponential cost trend, with costs ranging from US\$83 million to US\$501 million, and an average of US\$277.8 million. This decline may indicate technological maturity, standardization, and improved anomaly mitigation strategies in payload systems, resulting in a reduced financial impact over time, as designs have become more reliable, easier to test, and better equipped to handle minor issues before they escalate [25, 26].

The power subsystem displayed a generally stable cost pattern, with values between US\$96.6 million and US\$755.75 million, and an average cost of US\$288.2 million. Although most power-related anomalies result in moderate financial losses, a few significant spikes indicate that some failures, such as those involving solar arrays or batteries, can cause substantial economic damage. Finally, the attitude control subsystem reflected a moderate upward trend in cost, with anomaly-related expenses ranging from US\$159.25 million to US\$563 million, and an average of US\$272.4 million. This suggests that while attitude control issues are generally manageable, the critical nature of this subsystem in maintaining satellite orientation and mission continuity makes its failures progressively more expensive to address.

For the Weibull fit, it can be deduced that the antenna subsystem shows a steep Weibull rise, reflecting the consequences of anomalies that are likely tied to the growing complexity and importance of antenna systems in satellite missions. The payload subsystem follows a less steep trajectory, with costs spread more evenly, pointing to improvements in payload resilience or mission-specific impact. Power systems exhibit a Weibull curve with a long tail, suggesting most anomalies incur moderate costs but outliers remain highly expensive, particularly in newer, power-intensive missions [27]. Attitude control systems demonstrate more stable cost behavior, yet still with a rising trend, highlighting the non-negligible effect of pointing failures on mission performance.

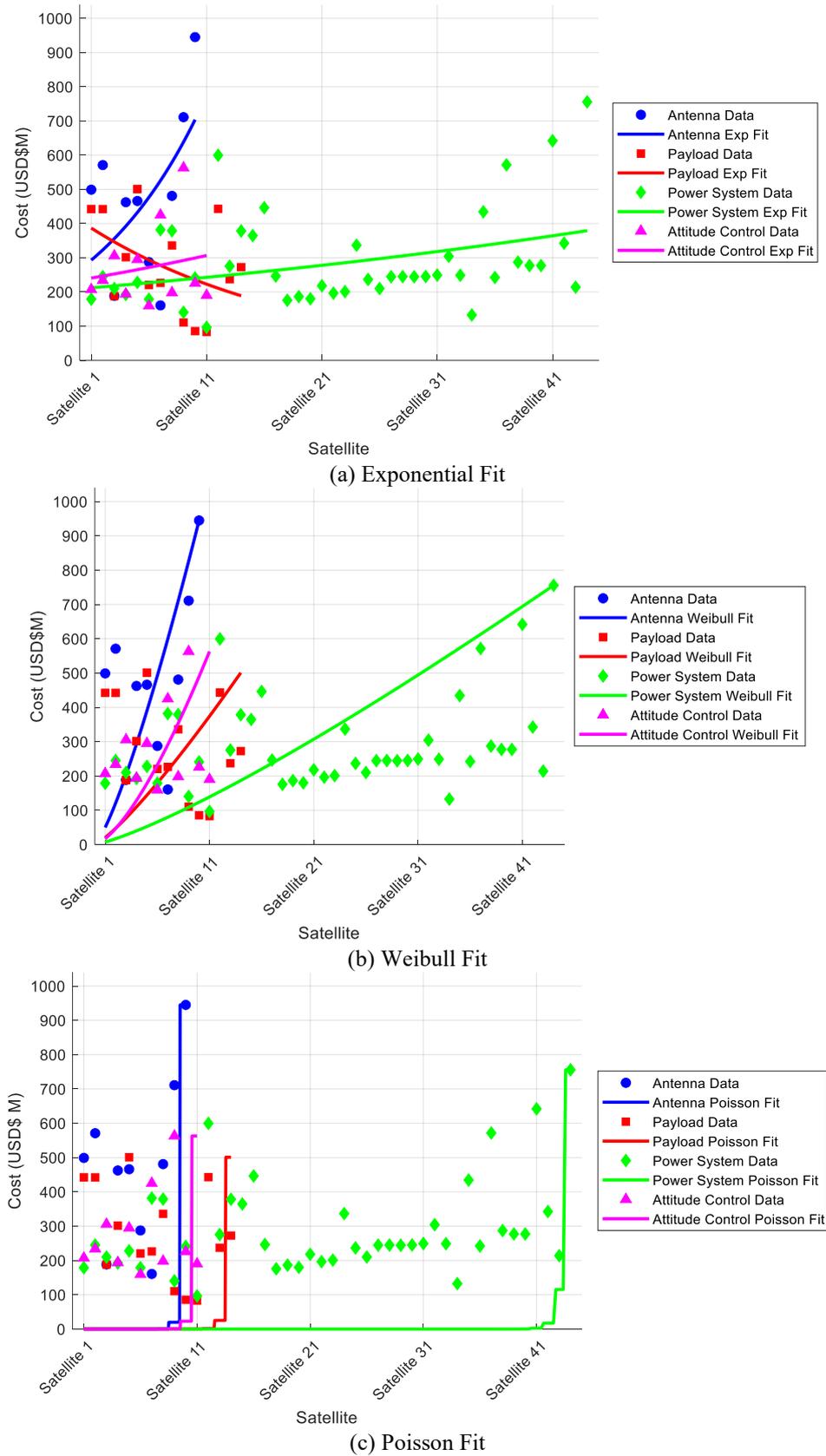


Figure 1. Cost Data for Various Fits

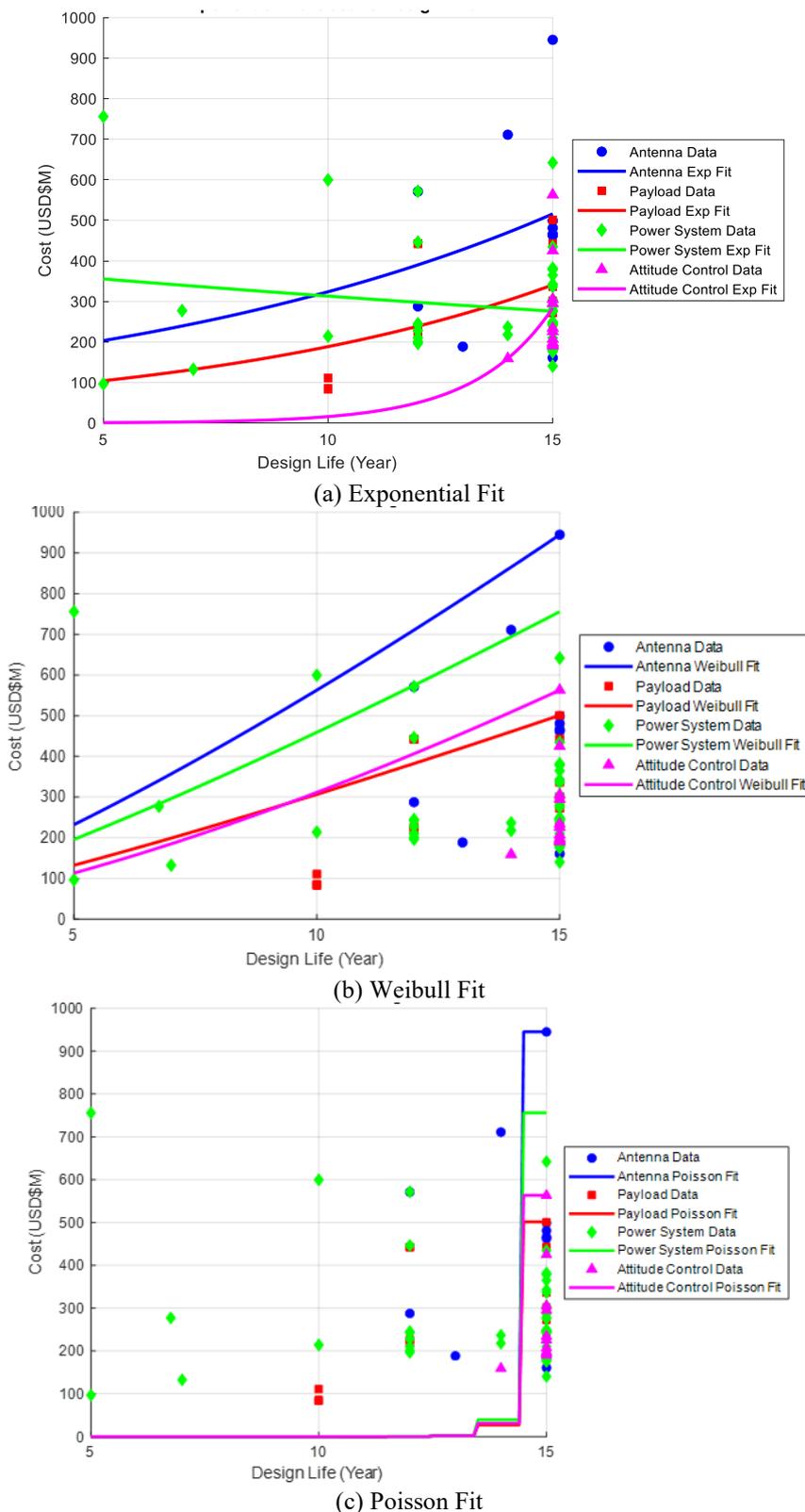


Figure 2. Cost vs Design Life for Various Fits

On the other hand, as shown in Figure 2, the Exponential model was applied to the cost versus design life data for each satellite subsystem. In Figure 2, 2 variables are used: design life and cost. The cost data is like a one-variable graph. For the antenna subsystem with a design life ranging from 12 to 15 years, the curve closely followed the upward trend in cost as design

life increased, indicating a strong fit. The payload subsystem with values from 10 to 15 years also exhibited a reasonable Exponential increase, suggesting a consistent relationship between longevity and investment. In contrast, the power system's fitted curve unexpectedly decreased with design life, with values ranging between 5 and 15 years. This does not align with engineering expectations and suggests that this subsystem may not suit an Exponential model. The attitude control subsystem, which has values only in 14 and 15 years, displayed an exaggerated rise in cost, possibly due to limited or uneven data in the higher design life range. The Exponential model worked best for the antenna and payload subsystems but was less reliable for the power system and attitude control components.

The Weibull model was applied to the cost versus design life data to evaluate its flexibility in modeling various subsystem behaviors. For the antenna subsystem with an average design life of 13.5 years, the Weibull fit produced a smooth upward curve that effectively captured the increasing cost trend. The payload subsystem with values between 10 and 15 years also showed a strong alignment between the fitted curve and the actual data, suggesting a consistent cost increase as design life extended. The power system's compromise of design life between 5 and 15 years, which did not follow the exponential pattern well, was better represented by the Weibull fit, which provided a realistic, gradual rise in cost. Similarly, the attitude control subsystem with values of 14 and 15 years demonstrated improved curve fitting, with the Weibull model managing to capture the cost behavior more smoothly than the exponential approach. Overall, the Weibull model offered better adaptability across all subsystems and was particularly effective in modeling the power system and attitude control costs.

The Poisson model was tested to explore its applicability to the cost versus design life data; however, the results revealed significant limitations. For all subsystems, which are antenna, payload, power system, and attitude control, with average values of design life of 13.5 years, 12.5 years, 10 years, and 14.5 years, respectively, the fitted curves resembled discrete step functions rather than smooth trends. This characteristic of the Poisson model led to poor alignment with the actual data, especially for subsystems like power system and attitude control, where the cost varied more gradually. Since the Poisson distribution is designed to model count-based events rather than continuous variables, such as cost, its application was conceptually mismatched. As a result, the Poisson model failed to provide meaningful or realistic predictions and was the least suitable option for this analysis.

Table 2. RMSE and RRMSE results

Subsystems	Model	RMSE (1 variable)	RRMSE (1 variable)	RMSE (2 variable)	RRMSE (2 variable)
Antenna	Exponential	194.94	71.56%	218.16	45.72%
	Weibull	271.85	99.80%	455.24	95.40%
	Poisson	431.14	158.27%	489.87	102.65%
Payload	Exponential	121.84	44.73%	115.73	41.66%
	Weibull	239.07	87.76%	186.21	67.03%
	Poisson	304.71	111.86%	240.17	86.45%
Power System	Exponential	128.17	47.05%	134.70	46.73%
	Weibull	229.69	84.32%	434.17	150.64%
	Poisson	295.86	108.61%	442.79	153.63%
Attitude Control	Exponential	114.15	41.91%	110.57	40.59%
	Weibull	194.22	71.30%	307.02	112.71%
	Poisson	310.01	113.80%	290.91	106.79%

After executing the models on the dataset, we evaluated their performance in predicting actual satellite subsystem costs. The Root Mean Square Error (RMSE) and Relative Root Mean Square Error (RRMSE) were used as the primary evaluation metric, as they quantify the average deviation between the predicted values and the observed data. A lower RRMSE indicates a better fit of the model to the actual cost values. Table 2 compares RMSE and RRMSE between all subsystems across the two types of graphs.

The Exponential distribution consistently provided the best fit among the models, especially when design life was used as a second variable [28]. This was particularly evident for the payload subsystem, where the Exponential model achieved the lowest RMSE and RRMSE values of 121.84 and 44.73% in the one-variable case, and even lower in the two-variable case at 115.73 and 41.66%, respectively. Similarly, for the attitude control subsystem, the Exponential model performed well, with an RMSE of 114.15 and an RRMSE of 41.91% in one-variable fitting, and showed slight improvement in the two-variable case, with an RMSE of 110.57 and an RRMSE of 40.59%.

On the other hand, the Poisson model consistently produced the highest errors across most subsystems. For instance, in the antenna subsystem, the Poisson model had an RMSE of 431.14 and RRMSE of 158.27% in the one-variable case, and even higher RMSE in the two-variable case at 489.87, though the RRMSE slightly decreased to 102.65%. This suggests that Poisson modelling does not effectively capture the relationship between the cost and design life of these components, likely due to its discrete nature and assumptions that don't align well with continuous cost behavior [29].

The Weibull model showed mixed performance. It performed moderately well for the payload subsystem, with RMSE and RRMSE of 239.07 and 87.76% (one-variable), and 186.21 and 67.03% (two-variable), indicating an improvement when a second variable is considered. However, for the power system, the Weibull model was less reliable in the two-variable case, with RMSE increasing from 229.69 to 434.17 and RRMSE jumping from 84.32% to 150.64%, showing it failed to capture the system's behaviour under more complex modeling. Overall, the Exponential model best represents the underlying relationship between subsystem design life and the associated costs, especially in the two-variable form. It offers the most consistent and lowest errors across multiple subsystems, making it a more reliable choice for cost modeling in satellite anomaly analysis.

5. CONCLUSION

This study focused on understanding how anomalies in critical satellite subsystems, including the antenna, payload, power system, and attitude control, relate to their design life and subsequent financial losses. Using data from the Seradata database, the research employed statistical modeling within a trade-space exploration framework to analyze cost behavior and failure patterns. The goal was to provide more accurate cost predictions and support better design decisions by considering both the technical and financial aspects of satellite performance. The exponential distribution consistently performed best in fitting the data among the models tested. It yielded the lowest RMSE and RRMSE values for most subsystems, particularly when design life and cost were combined in the two-variable fitting. This was particularly evident for the payload subsystem, where the exponential model achieved an RMSE of \$115.73 million and an RRMSE of 41.66%, and for the attitude control subsystem, with an RMSE of \$110.57 million and an RRMSE of 40.59%. These results indicate that the exponential model captures the trend of rising costs with subsystem aging more effectively than the other distributions. In comparison, the Poisson model performed poorly across all subsystems, with high RMSE and RRMSE values that indicated a weak fit. For instance, the

antenna subsystem reached an RMSE of \$489.87 million and RRMSE of 102.65%, highlighting its limitations when applied to continuous cost data. The Weibull model yielded mixed results, performing reasonably well for the payload subsystem with an RMSE of \$186.21 million and an RRMSE of 67.03%, but failed to provide reliable predictions for the power system and antenna subsystems, particularly in two-variable modeling, where errors increased. The findings highlight that choosing the right model is crucial when analyzing satellite reliability and anomaly-related costs. The exponential model is the most reliable and consistent, making it a practical choice for future studies and design planning. Ultimately, this study provides a valuable framework for optimizing subsystem design and managing risk by identifying where extending design life stops delivering proportional cost benefits.

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